DOES CROP ROTATION MAINTAIN THE FERTILITY OF THE SOIL?

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FROM time immemorial it has been considered a self-evident fact that where crop rotation is practised there is a bigger and better yield. The farmers of ancient Rome understood that crops following beans, peas and vetches were usually better than those following wheat or barley; but it was not until the last quarter of the nineteenth century that it was learned that the legumes with the aid of associated bacteria has the power of feeding on the free nitrogen of the air, while the non-leguminous plant has not this power and requires a supply of combined nitrogen. To-day we find the best farmers practising some system of crop rotation. They have learned from experience that where crop rotation is practised the crops are bigger and better than where the single crop system is followed. This is usually interpreted as indicating that crop rotation has increased the fertility of the soil. We find many farmers planting legumes for a number of years on rundown soil, each year removing the entire crop and feeling confident that their soil is becoming richer in plant food. Let us examine some of the results which have been obtained in carefully planned experiments to see if this conclusion is warranted by the experimental evidence.

Plants are composed of ten elements, each of which is absolutely essential to their growth and formation. Only two —carbon and oxygen—are secured from the air by all plants, only one—hydrogen—from the water; the other seven are secured by all plants from the soil. One class of plants—the legumes—may, under appropriate conditions, obtain their nitrogen from the air. Six elements—phosphorus, potassium, magnesium, calcium, iron and sulfur—are obtained entirely by the growing plant from the soil.

The great majority of agricultural soils contain large quantities of all these essential elements, with the exception of nitrogen, phosphorus and potassium. These are used by the growing plant in larger quantities than are any of the other elements which are obtained direct from the soil, and in the great major-

ity of soils nitrogen, phosphorus, or potassium is the limiting element in crop production. Therefore our problem resolves itself into the question: Can crop rotation maintain these elements in the soil in quantities sufficient for maximum yields? Phosphorus and potassium are obtained by the growing plant only from the soil; it is, therefore, self-evident that no simple system of crop rotation can maintain the phosphorus and potassium, since the quantity within the soil must of necessity be reduced with each crop removed; the extent depending upon the specific crop grown; hence, nitrogen is the only element which we can hope to maintain by crop rotation. This is the element which is found in the soil in smallest quantity and removed by most plants in larger quantities than the phosphorus or potassium. Moreover, large quantities of this element are at times lost from the soil by leaching, while the loss of the others is comparatively small. It is of the greatest importance, therefore, that nitrogen be supplied to the soils in sufficient quantities for maximum crop production and in the cheapest manner possible. The total quantity of these three elements found in an acre-foot section of two Utah agricultural soils, assuming one acre-foot to weigh 3,600,000 pounds, is given in Table I.

TABLE I. POUNDS PER ACRE OF TOTAL NITROGEN, PHOSPHORUS AND POTASSIUM IN AN ACRE-FOOT OF SOIL FROM THE UTAH GREENVILLE AND NEPHI EXPERIMENTAL FARMS

	Greenville Farm, Pounds per Acre	Nephi Farm, Pounds per Acre
Nitrogen	4,904	3,744
Phosphorus	2,700	8,388
Potassium	60,560	87,840

Both soils contain an abundance of potassium, but the supply of phosphorus and nitrogen is much lower. A study of these results reveals the fact that a fifty-bushel crop of wheat each year for forty-nine years would remove the equivalent of the total quantity of nitrogen in the Greenville soil to a depth of one foot, while a similar crop on the Nephi farm would accomplish this in just thirty-seven years. It would, however, require a fifty-bushel crop 170 years to remove the phosphorus from the Greenville soil and 525 years to remove it from the Nephi soils. Of course a crop would never remove all the nitrogen or phosphorus from a soil, but in actual practise the elements are slowly removed; the crop yields being reduced each year until a certain minimum is reached. When crops can no longer be produced economically then the owner abandons his

soil, moves on to virgin soils, or if it be in an old district he resorts to the expensive commercial fertilizer. The illustration is, however, sufficiently accurate to make it clear that the limiting factor, in so far as soil fertility is concerned in both of these soils, is the nitrogen. And it is true of the great majority of all soils that an increased nitrogen supply means an increased yield. This principle is one of the fundamentals of soil fertility.

Nitrogen exists in the atmosphere in inexhaustible quantities, every square yard of land has seven tons of nitrogen lying over it or if the quantity covering one acre could be combined into the nitrate it would be worth as a fertilizer $125,000,000. Now it has been demonstrated that the legumes—peas, beans, alfalfa, etc.—when properly infected have the power of feeding on this limitless supply of atmospheric nitrogen, while the non-legumes—barley, wheat, oats, etc.—must depend upon the supply within the soil. The farmer should take advantage of this fact to supply nitrogen for his crops, as the commercial fertilizer can not be used economically for the production of most crops, as is seen from the fact that the nitrogen in a 50-bushel wheat crop would cost $14.40, 20 tons of sugar beets $15.00 or one ton of alfalfa hay $7.50 if bought as a commercial fertilizer. But will the legume draw nitrogen from the atmosphere while there is a supply in the soil, or will it follow the line of least resistance and turn only to the atmosphere when nitrogen is lacking in the soil? If it does, it must first drain the soil of its valuable nitrogen and thus leave it no richer than it was before the legume was grown upon the soil. This is the problem which this paper is to answer.

Crop rotation has been practised for centuries, but the oldest system of which we have accurate information is the one on Agdell Field at the Rothamsted Experiment Station. This system was inaugurated in 1848 and is still being carefully followed. It consists of a four-year rotation as follows:

First year—Swede turnips (rutabagas)
Second year—barley
Third year—clover or beans
Fourth year—wheat

Still another system has been running parallel and similar to this, except that fallow cultivation is practised in the third year instead of growing a legume. The average yields for twenty-year periods are given in Table II. These systems are of especial interest to the farmers of Utah, for when we substitute sugar beets for the turnips, and alfalfa or peas for the clover or beans, we have nearly an ideal rotation for our soils.

TABLE II. AVERAGE 20-YEAR YIELDS FROM AGDELL FIELD, ROTHAMSTED STATION

Crop	Legume			Fallow		
	Yield 1st 20 Years, 1848–68	Yield 2d 20 Years, 1868–88	Yield 3d 20 Years, 1888–1908	Yield 1st 20 Years, 1848–68	Yield 2d 20 Years, 1868–88	Yield 3d 20 Years, 1888–1908
Turnips						
Roots pounds	5,264	1,723	967	5,785	3,067	2,502
Leaves pounds	600	447	242	629	538	458
Barley						
Grain, bus.	38.0	22.5	13.7	37.0	22.8	15.9
Straw pounds	2,373	1,496	1,172	2,244	1,489	1,172
Wheat						
Grain, bus.	29.6	21.1	24.3	34.5	23.2	23.5
Straw pounds	3,169	2,082	2,445	3,761	2,420	2,412

Even where the legume was used in the system there has been a decline in the yield. The yield of the turnips during the first twenty years was 5,264 pounds, the second 1,723, and the third only 967 pounds, thus showing a decrease to about one sixth the original in sixty years. The results with the barley are no better, for we find a drop from the fair yield of 38 bushels per acre during the first period to only 13.7 during the third. The wheat which followed the legume in the rotation, and hence occupied the most-favored place in the system, shows a decrease of 5.3 bushels. Not even a good yield has been maintained for the clover, for from 1850 to 1874 the average yield was 4,165 pounds, while from 1882 to 1906 the yield was only 1,246 pounds. In reality we find no greater decline in the yields where fallow cultivation is practised. But both systems strongly testify to the fact that rotation is not maintaining the productive powers of this soil. And the evidence is strong that the legume gets no more nitrogen from the air than that which is removed with the plant. Otherwise we should expect better results in the legume system than in the fallow system.

That the alfalfa, when grown on fertile soil and the crop removed, does not increase the nitrogen of the soil is seen from experiments conducted by Dr. Hopkins at the University of Illinois. The experiment was made possible by the fact that many of the Illinois soils do not normally contain the symbiotic bacteria thus making it impossible for the alfalfa to obtain nitrogen from the air. This being the case, a field was taken which had not grown alfalfa and hence did not contain the symbiotic nitrogen-gathering bacteria. This was planted to alfalfa, only one half of it being inoculated with the legume organism. To some of the plots were added lime and phosphorus to make sure that these were not the limiting factors. The results thus obtained are given in Table III.

TABLE III. FIXATION OF NITROGEN BY ALFALFA IN FIELD CULTURE, ILLINOIS EXPERIMENTS

Plot No.	Treatment Applied	Pounds in Crop		Pounds Nitrogen Fixed by Bacteria
		Dry Matter	Nitrogen	
1a.......	None	1,180	21.81	
1b.......	Bacteria	2,300	62.04	40.23
2a.......	Lime	1,300	26.20	
2b.......	Lime bacteria	2,570	68.02	41.82
3a.......	Lime phosphorus	1,740	35.40	
3b.......	Lime phosphorus bacteria	3,290	89.05	53.65

It is evident from these results that the alfalfa has obtained from 40 to 53 pounds of nitrogen from the air, depending upon the treatment. There was slightly more than one third as much nitrogen in the alfalfa crop from the uninoculated as in the inoculated. Therefore, it is quite evident that the alfalfa in these plots had obtained one third of its nitrogen from the soil and two thirds from the air. Now, nitrogen is required by the root for its growth as well as for the growth above the ground, and we have every reason for believing that the root also would obtain it in the same proportion from air and soil as did the hay crop.

Now, if we examine dry matter and total nitrogen occurring in the roots and stalks of alfalfa, we should be able to decide whether more nitrogen is being returned to the soil in the roots and residues than is removed by the growing plants.

The results for this comparison have been obtained from Illinois and Delaware experiments and are given in Table IV.

TABLE IV. PROPORTION AND COMPOSITION OF TOPS AND ROOTS OF SOME LEGMUES

Legume	Dry Matter per Acre, Pounds	Nitrogen per Acre, Pounds	Per Cent. of Total Nitrogen in Tops
Sweet Clover			
Tops	9,029	174	76
Roots and residues	3,748	54	
Crimson Clover			
Tops	4,512	103	70
Roots........................	2,022	41	
Alfalfa			
Tops	2,267	54.8	60
Roots........................	1,980	40.4	

With the clover three fourths of the total nitrogen is found in the plant above ground and only one fourth in the roots, while the alfalfa shows a greater proportion in the roots—40 per cent. This represents the proportion for the first-year growth for alfalfa and it is not likely that in the older plant this

high proportion of the total nitrogen would be maintained in the roots. It is quite certain that if only two thirds of the total nitrogen of the plant is obtained from the air the quantity returned to the soil with the roots and plant residues does not exceed that removed from the soil by the growing plant, which would give no increase in soil nitrogen from the growing of a legume where the entire crop is removed. And this even where the roots are allowed to remain and decay; yet we find some farmers who remove the roots from the soil and even then expect an increase in their soil fertility.

It is therefore quite certain that the legume, where the crop is harvested, does not increase the soil nitrogen of the fertile soil of Illinois and other soil fairly rich in nitrogen. But what will happen on the arid and semi-arid soil where nitrogen in many cases is the limiting element and is present in much smaller quantities than it is in the soils on which the experiments considered have been conducted. Experiments which have been conducted at the Utah Experiment Station during the last twelve years have demonstrated that even on soils poor in nitrogen the legume first feeds upon the combined nitrogen of the soil. It is known that plant residues and other complex nitrogen compounds found in the soil are transformed by bacteria into ammonia and this in turn by another class of bacteria into nitric nitrogen, and it is mainly on this nitrogen that the growing plant feeds. The quantity of this found in the soil at different periods under different plants has been measured at the Utah Experiment Station and the average results for twelve years are given in Table V.

TABLE V. NITRIC NITROGEN FOUND UNDER VARIOUS CROPS AT DIFFERENT SEASONS OF THE YEAR, POUNDS PER ACRE TO A DEPTH OF SIX FEET

Crop	Spring	Midsummer	Fall	Average
Alfalfa	22.3	15.8	32.8	23.6
Oats	35.7	14.1	20.6	23.5
Corn	24.8	18.9	22.0	21.9
Potatoes	81.1	60.8	54.2	65.3
Fallow	81.5	53.6	62.6	65.9

Here we find the legume alfalfa, removing the nitric nitrogen from the soil just as fast as do the non-legumes. Yet this soil was well inoculated with the symbiotic bacteria which undoubtedly assisted the alfalfa in obtaining free nitrogen from the air when needed, but not until the soluble nitrogen had been drained from the soil to its full extent, as is shown by the fact

that alfalfa soil never contains more than does oats and corn land and is very poor as compared with potato and fallow soil.

It may be argued that the small quantity of nitric nitrogen in the alfalfa soil is due to a lack of its formation, as it is not needed by the legume, hence not formed; but this conclusion is not warranted by the facts in the case, as may be seen from the results obtained where the speed of formation of nitric nitrogen (nitrification) was measured. These also are the average results extending over a number of years and obtained at the Utah Experiment Station.

TABLE VI. MILLIGRAMS OF NITRIC NITROGEN PRODUCED IN 100 GRAMS OF SOIL IN 21 DAYS

Crop	Spring	Midsummer	Fall	Average
Alfalfa	3.15	7.48	3.08	4.56
Oats	2.40	4.00	3.00	3.13
Corn	2.18	3.50	1.48	2.38
Potatoes	3.00	15.55	5.60	8.04
Fallow	1.30	5.50	2.48	3.09

Here we find the quantity of soluble nitrogen produced in the alfalfa soil greater than that produced in either the oat or alfalfa soil, and there is no doubt but that this is one reason why an increased yield is obtained the year following the plowing up of an alfalfa field; for this increased nitrification is noted for several years after an alfalfa field is planted to some other crop. This is due to the alfalfa plant stimulating bacterial organisms of the soil so they make available faster the nitrogen of the soil, but this only depletes the soil of its nitrogen more readily than does the non-legume, for it is the nitrogen already combined in the soil on which the nitrifying organisms act. Hence, we must conclude that alfalfa not only feeds closer on the soluble nitrates of the soil, but it also makes a greater drain upon the insoluble nitrogen of the soil by increasing the nitrifying powers of the soil, and would therefore deplete the soil, if the entire crop be removed, more readily than would other crops, a conclusion which is borne out by the direct analysis of the soil. For the analysis of a great number of Utah soils which have grown various crops for a number of years—some of them having been into alfalfa or wheat for upward of thirty years—revealed the fact that almost invariably the alfalfa soil contained less total nitrogen than did the wheat soil. The average for a great number of determinations made from alfalfa soils was 7,232 pounds per acre of total nitrogen, while

the average for a great number of wheat soils was 7,398 pounds.

These are average results from a great number of determinations made on adjoining alfalfa and wheat soil and they clearly indicate that in ordinary farm practise the alfalfa is making just as heavy a drain upon the soil nitrogen as is the wheat.

Hence, from a consideration of the yields obtained in crop rotation, the relative quantities of nitrogen obtained from the atmosphere and the soil by the alfalfa, the feeding and stimulating effect of the alfalfa upon nitrates, and finally the actual quantity of total nitrogen remaining in the soil after wheat and legumes, we must conclude that the legume does not increase the nitrogen of a common agricultural soil—even in the arid region where the nitrogen is low—when the entire crop is removed.

This conclusion does not, however, mean that crop rotation should not be practised, for there are many reasons why crop rotation commends itself to the careful farmer, but it must not be used and the legume removed with the intention of maintaining soil fertility. This may appear to be an unfortunate conclusion, but it is just the reverse, and if its teachings are heeded it means a fertile soil and an economic gain to the farmer from the system of farming which it requires him to adopt.

There are two practicable methods of maintaining the nitrogen content of the soil. First, planning systems of crop rotations with legumes, the legumes being plowed under and allowed to decay, thus furnishing nitrogen to the succeeding crop. Second, practising a combined system of crop rotation and livestock farming.

Three tons of alfalfa contain 150 pounds of nitrogen, all of which we could assume came from the atmosphere; assuming the quantity found in the roots as coming from the soil. This is the equivalent of the nitrogen found in the grain and straw of seventy-five bushels of wheat. If the alfalfa is plowed under some of the nitrogen would be lost to the growing plant in the processes of decay and leaching, but that the total nitrogen of the soil may actually be increased by the turning under of the legume is certain from field experiments.

The Dominion of Canada Experiment Stations grew mammoth clover for two successive seasons on a soil very low in nitrogen. The two cuttings of mammoth clover with all the residues were turned under each year with the results that the soil gained as an average 177 pounds per acre of total nitrogen which is the quantity of nitrogen found in three forty-bushel

crops of wheat, provided the straw was returned to the soil, as two tons of this contains 20 pounds of nitrogen. On the other hand, work on the soil of the Utah Nephi Experiment Farm, with a rotation of wheat and peas where the peas were plowed under, showed a gain in total nitrogen of 240 pounds in four years. That is, in addition to furnishing the small quantity of nitrogen required by the wheat crop, the peas had added to the soil an average of 60 pounds of nitrogen per year.

The second method of maintaining the nitrogen and organic matter of the soil—the combined rotation and livestock method—is the more practical and if systematically practised will not only maintain the nitrogen of the soil but will prove of great economic value to the individual following it. For it consists of a rotation in which the legume plays a prominent part. The legume to be fed and all the manure returned to the soil: This would mean the selling from the farm the hay crop in the form of butter, milk, or beef which carries from the soil only a fraction of the nitrogen stored by legume; moreover, it brings for the producer much greater returns than does the system in which the legume is completely removed from the soil.

It must, however, be remembered that in this system only about three fourths of the total nitrogen of the feed is recovered in the dung and urine. So that in place of three tons of alfalfa adding 150 pounds of nitrogen to the soil from the air, it would add only 120 pounds and this on the condition that all of the liquid and solid excrements are collected and returned to the soil. But where the alfalfa is to be fed and the manure returned to the soil, the legume can occupy a much longer period in the rotation and that with greater economy than where the legume is to be plowed under directly.

Hence, we find that if these principles which have been established for soils even low in nitrogen be systematically applied it will result in greater revenue from an increased livestock industry and will maintain the soil rich in nitrogen and organic matter in place of depleting it of its stored-up nitrogen, as is so often the case with the present methods.